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THE ROLE OF MANUFACTURING DEFECTS IN MUNITION COMPONENT FAILURES

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Abstract: The US Army Research Laboratory performs numerous failure analysis investigations on munition-related components. Many of these failures are attributable to defects that can be traced back to the manufacturing process. This paper will discuss the impact of these defective parts making their way into service. Munition component failures are very costly, and may seriously affect the safety and readiness of the fleet, as well as leading to a system grounding depending on the severity of the problem. Typical defects included those associated with the material, forging, casting, welding, and heat treatment processes. Also, dimensional anomalies have been noted. Specific examples of component failures will include bomb fin retaining bands, general-purpose bomb suspension lugs, missile launcher attachment bolts, cluster bomb tailcones, general-purpose bomb fins, and Gatling gun breech bolt assemblies. In addition, this paper will focus on the importance of proper manufacturing techniques in this industry.

Key Words: Failure Analysis; Metallurgical Investigation; Flight Safety Critical Components, Manufacturing Defects

COMPONENT: MK 15/Mod 6 Snakeye Bomb Fin Retaining Band
MANUFACTURING DEFECTS: Improper heat treatment / Improper dimensions

Background: A retaining band from the MK15 Mod 6 Snakeye bomb fin unwrapped during a practice flight, causing the bomb fins to deploy, as well as triggering an adjacent retaining band to become unraveled. The pilot was able to land without incident, and upon inspection of the bomb fin, it was noticed that the retaining band had not actually broken, but had simply loosened from its original tightened position.

ARL Investigation: The Naval Air Warfare Center (NAWC) sent the "failed" as well as, an intact retaining band to ARL for inspection and analysis. Chemical analysis, dimensional verification, hardness testing, metallography and tensile testing were performed in order to determine the cause for premature failure.

Results of Investigation: The chemical composition of the components compared favorably to Type 302 stainless steel, which conformed to the governing requirement (Type 301 or 302). Dimensional inspection revealed that the band was thinner than required. The results of hardness testing were lower than required, and compared more favorably to the material in the annealed condition, rather than the ¼-hard condition that was required. Metallography results were in agreement with the hardness results, as the grains of the Type 302 stainless steel were equiaxed, rather than flattened, or "pancaked" (see Figure 1). Tensile testing confirmed that the component was annealed, as the results did not compare favorably with those for the ¼-hard condition.

Effect of Manufacturing Defect on Performance: The retaining band was able to unwrap itself from the clamp tightener because it was thinner than required, and softer (less stiff) than intended.

Outcome: The NAWC is going to scrap the retaining band kits fabricated by the manufacturer of the suspect kits, and procure new components. They will oversee the manufacturers procedures and perform first article testing to ensure this type of situation does not occur again.

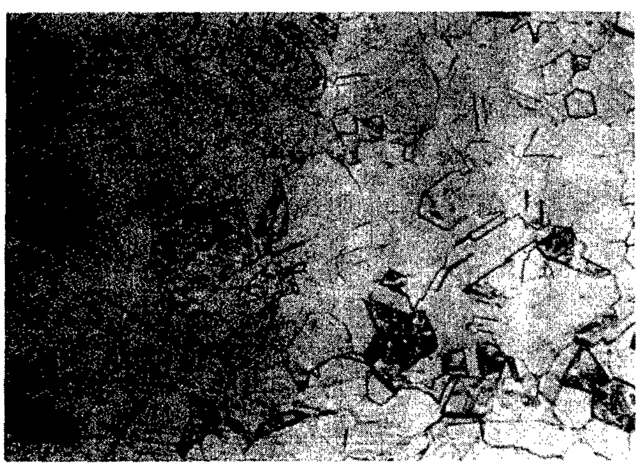

Figure 1 Micrograph showing the equiaxed grains of the Type 302 stainless steel, typical of the annealed condition. Mag. 400x.

COMPONENT: MS3314 General-Purpose Bomb 1,000-Pound Suspension Lug
MANUFACTURING DEFECTS: Forging Laps and Seams

Background: Two MS3314 suspension lugs are threaded into each general-purpose bomb, such that the munitions can be loaded onto the underside of Navy aircraft. A total of three AISI 4340 MS3314 suspension lugs failed during routine proof load testing. The proof load testing required the part to sustain a tensile load of 35,000-pounds for one-minute at a 6-degree angle, as well as 24,000-pounds at a 35-degree angle for one-minute. These three lugs failed to achieve the one-minute duration before failure occurred.

ARL Investigation: Two of the three failed lugs were sent to ARL from the Naval Air Warfare Center (NAWC) for failure analysis. The failure investigation included visual examination, chemical analysis, metallography, hardness testing, scanning electron microscopy, and energy dispersive spectroscopy.

Results of Investigation: Visual examination revealed a blackened region at the crack origin of each failure. In addition, a forming lap was found on the external bail surface of one of the failed lugs. Material sectioned from the failed lugs and subjected to chemical analysis conformed to governing specification. Metallographic examination adjacent to the blackened regions at the crack initiation sites showed slight carburization upon etching. This indicated that the regions were exposed to the high temperatures associated with the heat treatment. The hardness of the component was acceptable. Electron microscopy of the blackened surface revealed a featureless condition associated with oxide formation. It was concluded that the lugs failed due to overload conditions, as determined by the predominantly ductile dimpled fracture surface. Energy dispersive spectroscopy of the blackened regions revealed evidence of a corrosion product or heat treat scale.

Additional Testing: ARL performed the required proof testing on a number of lugs in inventory in order to determine the extent of the manufacturing defects. When many components failed the proof testing, it necessitated a magnetic particle inspection (MPI) screening of the hundreds of thousands of lugs in inventory. Figure 2 is a blacklight photomacrograph showing an example of a forging lap contained within the bail of a lug subjected to this screening. Concurrently, ARL and NAWC representatives visited the manufacturing facility in order to determine how the defective parts had made their way into inventory. It was determined that the contractor was not using an authorized written procedure for MPI. In addition, the contractor was using a system that was not capable of detecting defects in certain orientations. Further, poor lug handling practice was observed during the MPI process. This combination of factors allowed defective components to leave the facility undetected. As for the forging, the manufacturer took steps to minimize the amount of defects, including the use of a lubricant and decreased impact energy.

Effect of Manufacturing Defects on Performance: A lap is caused by the folding over of metal into the surface of the part during forming [1], while a seam is a discontinuity in a part caused by an incomplete joining of material during forming [2]. As shown in proof testing, the lugs were very sensitive to these surface anomalies. It was fortunate that defective lugs were revealed as a result of this proof testing (which is performed on a sampling basis), rather than in service.

Outcome: An extensive lug screening process was undertaken, whereby the parts that were previously magnetic particle inspected were subjected to an additional inspection consisting of a central conductor shot and a head-shot. The handling of the lugs subsequent to inspection was also improved, in an effort to reduce the masking of defective parts. Thousands of lugs were scrapped as a result of this re-inspection, and the warranty clause was invoked by the NAWC.

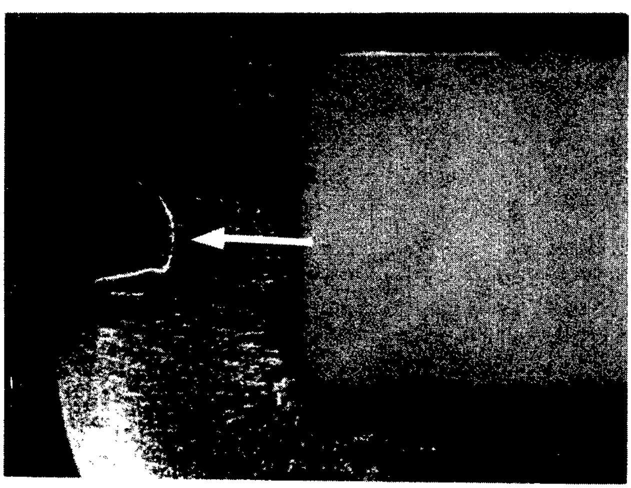

Figure 2 Blacklight macrograph showing typical lap defect within the bail region. Mag. 3x

COMPONENT: LAU-7 Missile Launcher Attachment Bolts
MANUFACTURING DEFECTS: Machining Rather Than Forging, Inadvertent Carburization

Background: Two LAU-7 missile launcher attachment bolts were found broken at Oceana, Virginia during pre-flight inspection. The bolts were installed on the aircraft for a total of two months before the failure was noted. The component is used to attach the missile launcher rails to the underside of Navy fighter aircraft, and is fabricated from Hy-Tuf® steel (AISI 4340 derivative). The bolts were required to be vacuum cadmium coated.

ARL Investigation: The failed bolts were sent to ARL from the Naval Air Warfare Center (NAWC) for failure analysis. The failure investigation included visual examination, metallography, chemical analysis, fractography, hardness testing, and stress durability testing.

Results of Investigation: Metallography and hardness testing revealed that the bolts were inadvertently carburized, which was not in conformance with the governing requirements. Additionally, macroetching revealed that the parts were machined from stock (rather than forged) and the threads were cut (rather than rolled). Figure 3 shows the etched grain flow within the threads. The rolling process would have produced a grain flow that followed the contour of the threads, however, the grain flow in Figure 3 does not follow the contour. It was determined that hydrogen-assisted stress corrosion cracking (SCC) was the probable cause of failure in both bolts. Hydrogen charging resulted from the surface corrosion. Contributing factors to SCC included surface carburization and the unacceptable grain flow pattern. Carburization resulted in a much harder (less tough) surface, while the stress distribution within the bolt head was adversely affected by the improper grain flow.

Additional Testing: As previously mentioned, stress durability testing was conducted on bolts from inventory to verify that the parts did not fail due to hydrogen charging from the plating process (in the case that the parts were electroplated rather than the required vacuum coating). The bolts were loaded to 80% of the UTS, and sustained for 200 hours. No failures occurred as a result of this testing. Also, ARL examined a number of bolts from different manufacturing lots for carburization and grain flow, in an effort to verify the extent of the problem. ARL was able to identify specific heat lots that were affected, and recommend others for continued use.

Effect of Manufacturing Defects on Performance: The forging process results in a grain flow that follows the contour of the part, and offers three distinct advantages compared to a part that was machined; enhanced directional strength, structural integrity and dynamic properties [3]. By refining the grain structure and developing optimum grain flow, forging promotes desirable directional properties such as tensile strength and ductility, and dynamic

properties such as impact toughness, fracture toughness and fatigue strength. With respect to structural integrity, forged parts are generally free from voids and porosity. All of these properties for the bolts under investigation were compromised as a result of the parts being machined rather than forged. The same advantages apply to threads that are rolled rather than cut. Carburization raises the surface hardness of the part, and is usually beneficial with respect to surface wear and fatigue resistance. However, the increased surface hardness made these components more susceptible to hydrogen attack.

Outcome: As mentioned, ARL offered a short-term recommendation concerning which bolts to continue using, and a long-term recommendation to consider changing the bolt to a lower strength (higher ductility, fracture toughness) material.

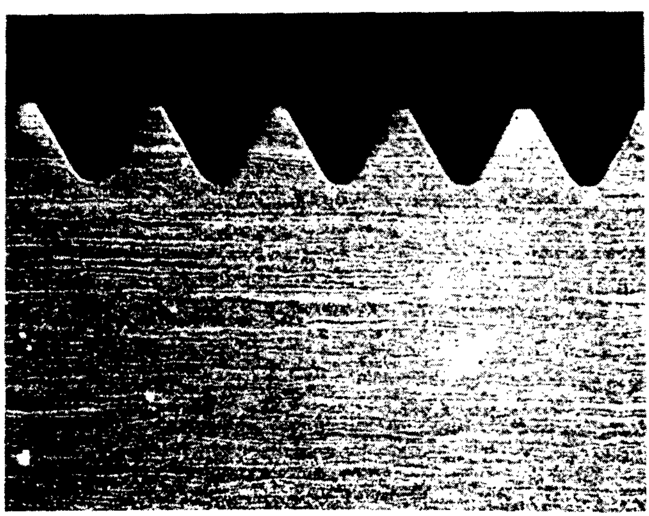

Figure 3 Macrograph showing the grain flow within the threads of the LAU-7 bolt. Note the flow does not follow the contour of the threads, indicating the threads were cut (machined) rather than rolled. Mag. 12.5x.

COMPONENT: Rockeye XVI Cluster Bomb Tailcone Assemblies
MANUFACTURING DEFECTS: Casting Heat Checks, Inclusions, Porosity and Shrinkage

Background: ARL conducted an analysis of two semicircular aluminum die-castings (alloy A356) that are components of the tailcone assembly of the Rockeye XVI Cluster Bomb. As the name implies, these components are located in the aft section of the bomb. The parts were rejected as unserviceable but repairable by the NAWC based upon a surface condition noted during visual examination of the tailcones in inventory, and sent to ARL.

ARL Investigation: At ARL, the two tailcones were subject to visual and radiographic inspection, chemical analysis, metallographic examination, hardness testing, tensile testing and scanning electron microscopy with energy dispersive spectroscopy.

Results of Investigation: Visual examination revealed the presence of "heat checks" (Figure 5) on the surface of the tailcones, while radiography showed indications of foreign material (both more and less dense than the casting material), gas holes, and shrinkage defects. Tensile testing showed that the specimens fabricated from the components did not meet the required mechanical properties for this alloy. In some cases, the tensile failures initiated at large inclusions.

Additional Tasks: As a result of these findings, an inspection was performed at the component manufacturing facility. A tour was given of the entire production process, whereby it was witnessed that hardened slag products along the outside of the crucible were inadvertently being poured into the casting die with the molten metal. It was concluded that this may have attributed to the inclusions noted in the two tailcones that were examined. Recommendations were provided concerning this condition, as well as the presence of heat checks. To determine the extent of this casting problem, twelve tailcone sections from inventory were sent to ARL for analysis, similar to that performed on the two original tailcones. Several of these components exhibited shrinkage cavities, gas holes, and most failed to meet the required mechanical properties.

Effect of Manufacturing Defects on Performance: Heat checks are most often located on surfaces that correspond to areas in the die which are subject to high thermal stresses or where the liquid metal flows at high speeds causing erosion of the mold or die cavity [4]. These defects can also be caused by extended mold usage or die wear, and are open to the surface, resulting in decreased structural integrity. Gas holes (porosity) are generally formed by an excessive amount of gas in the metal bath, which is released during solidification. This defect reduces the cross sectional area of the component. Shrinkage typically occurs in the last areas to solidify, or areas in contact with gates. This defect reduces the cross sectional area of the component to a greater extent than porosity. In

aluminum die casting, especially Al-Si-Cu alloys containing iron (alloy of parts under investigation) intermetallic compounds (Fe-Al-Mn-Si combinations) which form locally or throughout the melt in the forms of grains or needlelike crystals because of excessively low temperature in the crucible holding furnace [5]. This was the situation noted at the manufacturer. As shown, these inclusions were present on the fracture surface of the tensile specimens, and most likely played a role in failure location.

Outcome: Not only did the components fail to meet the required mechanical properties, but the workmanship of the parts was less than acceptable. The extended analysis performed by ARL indicated that the problem was rather widespread. It was concluded that the serviceability of the casting was adversely affected as a result of these findings.

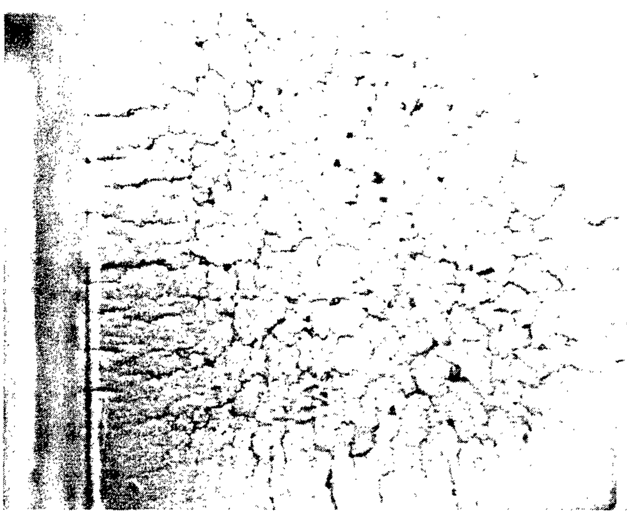

Figure 4 Macrograph showing the heat checks noted on the tailcone sections. Mag. 1.8x.

COMPONENT: MK 83 and MK84 General Purpose Bomb Fins
MANUFACTURING DEFECT: Non-Penetrating Spot Welds

Background: A First Article Inspection was performed for the MK83 and MK84 conical bomb fins. It was noted upon visual examination at the manufacturing plant that the chamfered butt welds (fusion weld) and the plug welds (resistance weld) showed less than optimal workmanship. The plug welds attach the outer skin to the inner spar, while the chamfered butt weld attaches the skin to the ring that is used to secure the fin to the bomb. The skin and associated components are made of low carbon steel.

ARL Investigation: Several of each type of conical fins was shipped to ARL for examination. Among other characteristics, the integrity of both the chamfered butt weld and the plug welds was examined. ARL performed radiography, tensile testing, visual examination and metallography of the failed test specimens in order to characterize the weldments.

Results of Investigation: Radiographic examination did not reveal significant nonconformities within the welds. Initial peel tests resulted in sheared spot welds, and unacceptably low loads. Figure 5 shows an example of a sheared plug weld. Note the burning that occurred on the underside of the parent material, indicating a lack of control. The process was improved, however, subsequent peel testing revealed a lower than nominal nugget size and corresponding lower than nominal pull loads for the plug welds. The tensile data from the butt welds conformed to the governing requirements. Visual and metallographic examination confirmed inadequate plug weld penetration. Visual examination of the sectioned fins also revealed cracked welds prior to tensile testing, plug welds that were misaligned with the intended positioning, and only partially attached plug welds to the spar. The data and photos were presented to the contractor, and the plug welding process was further improved. Not only were the through-holes for the plug welds enlarged, welding parameters were altered to allow for increased depth of penetration (i.e. increased dwell time, and increased current). This resulted in acceptable welds.

Effect of Manufacturing Defects on Performance: In general, the minimum depth of fusion is generally accepted as 20 percent of the thickness of the thinner piece [6]. The depth of fusion of the parts in question was much less than this amount, indicating less than adequate heating during welding. Since these welds were of inferior quality, the peel strength and the nugget diameters were well below the specified requirements. This may have led to eventual failures during service or storage.

Outcome: As mentioned previously, the spot weld dwell time was increased, as well as the current used to perform the welding. Since this anomaly was noted during a First Article Inspection of the manufacturing plant, none of the defective parts made their way into service.

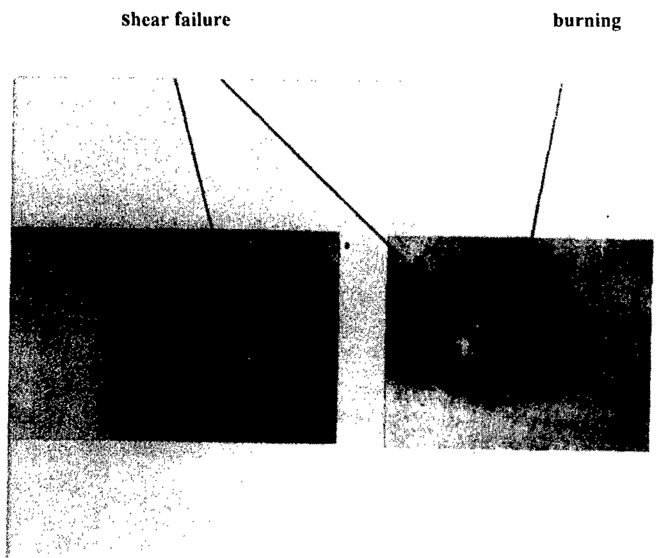

Figure 5 Micrograph showing shear failure of a resistance plug weld. Mag. 1x.

COMPONENT: M61A1 Breech Bolt Assembly
MANUFACTURING DEFECT: Improper Chemistry, Heat Treatment

Background: ARL characterized unused and failed "after-market" breech bolt assemblies from the M61A1 Gatling gun used on F-14 and F-18 Navy fighter jets. In addition, an individual locking block was examined. Similar components had exhibited accelerated wear during F-14 gun mount firing tests conducted at NAWCAD, Patuxent River.

ARL Investigation: A multitude of tests were performed at ARL to characterize the aforementioned components. The entire breech bolt assembly was subjected to a continuity test and a high voltage test, while the firing pin protrusion was measured in the locked and unlocked position. The component was subsequently disassembled, such that the individual components could be examined. The following analyses were conducted on the individual components; visual examination, surface finish, dimensional verification, magnetic particle inspection, metallography, chemical analysis, microhardness testing, macrohardness testing, coating thickness (where applicable), decarburization measurement (where applicable), case depth (where applicable) and double shear testing (where applicable).

Results of Investigation: Visual examination of the individual locking block revealed corrosion and a rougher than nominal surface finish. Metallography revealed a *complete* layer of decarburization along the periphery of the component, which was prohibited according to the governing specification. The depth of decarburization was greater than specified (0.006 vs. 0.003-inch). Hardness testing showed that the entire component (not just the area above the bail, as specified) was hardened to 50 – 55 HRC, not 38 – 43. Hardness testing also showed a loss of surface hardness due to the presence of the decarburization (~20 HRC at the surface, as opposed to 50 – 55 HRC elsewhere). *Figure 6* shows a Knoop microhardness profile through the decarburized layer. Note the larger surface readings corresponding to a lower hardness. In addition, the unused top and bottom bolt shafts were not nitrided, as confirmed through metallography and microhardness testing. These components also had a higher than specified silicon content by almost double. Finally, both of the spiral spring pins failed to achieve the 3,900-pound double shear load. One of these pins contained carbon approximately 10 times the requirement, which could have attributed to the poor double shear results.

Additional Tasks: ARL also examined a bolt shaft that had failed while in service. The results showed that the component failed due to fatigue. In addition, the part was not nitrided as required, which most likely led to the premature failure.

Effect of Manufacturing Defects on Performance: With respect to chemistry, the silicon content of maraging steels should not exceed the maximum limit, since the notch tensile strength [7], as well as the toughness [8] have been shown to be detrimentally affected. Concerning heat treatment, decarburization is a loss of carbon from the surface of a hardened steel part usually caused by an excessively high dew point or low carbon potential during the diffusion portion of a carbide-diffuse cycle, or of prolonged reheating in moist air or other decarburizing gas [9]. A complete decarburized layer consists of ferrite, which transitions to a layer of ferrite plus a low-carbon martensite towards the core of the component, followed by the normal tempered martensitic structure. The presence of decarburization acts to lower the surface hardness of a component, as was shown during the ARL analysis. Decarburization also affects the wear and fatigue resistance of a component. Finally, the effect of a lack of nitriding on a maraged steel component was shown by the in-service fatigue failure. Nitriding of maraging steels is performed to provide resistance to wear and fatigue [10], and should not have been neglected given the application.

Outcome: The quality and workmanship of the "after-market" components were poor, and these components should never have made there way into service. A First Article Inspection at the "after-market" manufacturing facility should have revealed these detrimental anomalies. The ARL results were presented to both the Air Force (procuring activity) and the NAWC (receiving activity).

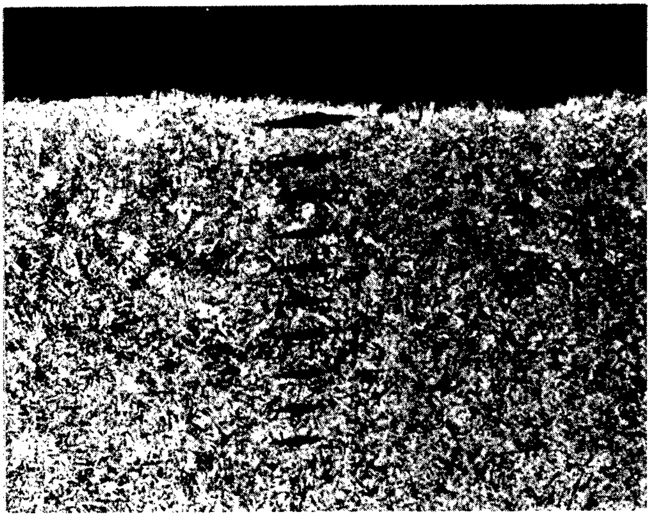

Figure 6 Microstructure of a locking block that contained decarburization. Note the softer surface indicated by the larger Knoop microhardness readings. Mag. 200x.

Conclusion: As shown in these few examples, manufacturing defects have the potential to negatively impact parts that are able to make their way into service. It is the responsibility not only of the manufacturer to adhere to quality workmanship practices, but also of the procuring activity, to ensure such defects are noticed prior to purchase and fielding of the parts. For the Department of Defense, this screening process is known as the First Article Inspection, where manufacturing processes (such as forging, casting, heat treatment, welding, etc.) and fabricated components are scrutinized prior to the start of final production. This inspection is intended to ensure conformance to the governing engineering drawings and specifications.

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